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TECHNICAL NOTE

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A HIGH-VELOCITY GUN EMPLOYING A

SHOCK-COMPRESSED LIGHT GAS

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A HIGH-VELOCITY GUN EMPLOYING A SHOCK-COMPRESSED LIGHT GAS

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SUMMARY

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A light gas gun is described which is relatively simple in construction and operation. Projectiles of 20-mm diameter are launched by helium which has been compressed and heated by a two-stage shock process. An explosion of powder is the primary source of energy. The operating cycle is distinguished by a light piston which operates in the second-stage shock tube and travels at supersonic speed with respect to the helium ahead of it. Muzzle velocities of over 20,000 feet per second have been obtained with light projectiles. Experience gained in firing over 400 rounds from this gun indicate that it is dependable enough for routine operation and should be a useful launcher for the investigation of various high-velocity phenomena.

INTRODUCTION

The gun described in this report was constructed for launching models in the Atmosphere Entry Simulator at the Ames Research Center. It has been found satisfactory for projecting light models at muzzle velocities of 12,000 to 22,000 feet per second, is simple in operation, and is capable of firing several rounds per day on a routine basis. A gun of this type may have other applications such as launching models in ballistic ranges for aerodynamic investigations or for impact studies. Hence, it is thought worthwhile to make a description of the construction, operation, and performance of the gun generally available.

The medium used for launching the projectiles is helium which has been compressed and heated by a shock process in two stages. Hence, the gun may be termed a two-stage shock-compression light-gas gun. It forms a logical development of the gun described in reference 1, where a single stage of shock compression was employed.

The principles underlying the use of a gas of low molecular weight, such as helium or hydrogen, as a medium for launching projectiles at high velocities have been discussed in reference 2 and elsewhere. The conclusion reached is that for a given maximum pressure of the driving gas entering the breech of a launch tube, the highest projectile velocity will be achieved by use of a gas of the lowest molecular weight and the highest temperature. The gun under consideration here, however, differs from that described in reference 2 in that a shock process, rather than an isentropic process, is employed in compressing the light gas. The required apparatus is smaller and less expensive, for reasons which will be discussed later.

SYMBOLS

P_1 initial pressure of helium in first shock tube

P_2 initial pressure of helium in second shock tube

P_B peak pressure at breech of first shock tube

P_C peak pressure at muzzle end of first shock tube

P_L peak pressure at muzzle end of second shock tube

CYCLE OF OPERATION

The arrangement of the gun is shown schematically in figure 1. It consists of two shock tubes and a launch tube arranged in descending order of diameter. The source of energy is a charge of smokeless powder placed in the breech end of the first shock tube. The two shock tubes are filled with helium to a pressure of the order of 200 or 300 pounds per square inch and are separated by a light piston. The projectile is placed at the breech end of the launch tube and is held in place by a light shear disk which may be integral with the projectile or separate.

A qualitative description of the firing cycle is as follows: When the powder charge is fired, a shock wave forms which travels down the first shock tube and is reflected from the partially closed end, giving for a brief time a reservoir of compressed and heated helium which drives the piston down the second shock tube. The velocity of the piston increases rapidly and after a short travel exceeds the speed of sound in the undisturbed helium. A shock wave of progressively increasing intensity then precedes the piston down the second shock tube. It is reflected from the partially closed end of the tube, raising the pressure and temperature of the helium in this part of the tube. The sudden rise in pressure causes the shear disk restraining the projectile to fail and the projectile is accelerated down the launch tube. The reflected shock wave meanwhile has met the advancing piston and is reflected, perhaps several times between the face of the piston and the end of the shock tube. Each time the shock wave traverses the helium, the pressure and temperature are raised, providing a reservoir of helium of rising pressure and temperature to flow into the launch tube to maintain, at a high value, the pressure acting on the base of the projectile, thereby accelerating the projectile to a high velocity. The helium from the second shock tube continues to flow into the launch tube until the piston reaches the end of the tube.

In order to realize the cycle of operation just described, the proportions of the tubes and the loading conditions must be kept within certain limits. The powder charge and initial helium pressure must be such that an intense shock is produced in the first shock tube. The piston weight must be small enough so that its speed greatly exceeds the speed of sound in the undisturbed helium ahead of it, but large enough so that its kinetic energy will be effective in raising the pressure and temperature of the helium in the second shock tube as the piston is brought to rest. The initial shock which strikes the base of the projectile must not result in too high a pressure or the projectile will be destroyed by shock or crushing. The maximum pressure at the entrance to the launch tube must be reached very quickly after the projectile starts to move or it will not be effective in increasing the projectile velocity as explained in reference 2 (pp. 53-56).

The operating cycle is difficult to analyze quantitatively because in the first shock tube the powder burns over a finite period of time; hence the shock is driven by powder gases of increasing pressure, and the maximum pressure measured at the breech cannot be used to predict, by conventional shock-tube calculations, the pressure after reflection of the first shock. Likewise in the second shock tube the division of energy between the moving gas and piston makes difficult the prediction of the pressure reached at the entrance to the launch tube. A few cautious trials, however, serve to establish experimentally the loading conditions which result in pressures and temperatures giving useful projectile velocities but within the strength limits of the apparatus.

In comparing the operating cycle of the present gun with the isentropic compression cycle described in reference 2, some advantages and some disadvantages are apparent. In order to obtain a given final temperature of the helium a much smaller compression ratio is required by the shock cycle than by the isentropic compression cycle; hence the required volume of the pump tube (in this case the second shock tube) is very much smaller than the pump tube of the comparable isentropic-compression gun. In addition, the pressure peaks in the present gun are of very short duration so that the gun is restrained primarily by its inertia and no large external reactions are generated. A disadvantage of the present gun is that the pressure of the helium at the entrance to the launch tube is maintained near its peak value for only a short time because of the low inertia of the piston and gases behind it. Therefore this cycle appears attractive for launching light projectiles only.

DESCRIPTION OF GUN AND APPARATUS

The dimensions of the present gun were chosen after a few trials with a smaller prototype made by adding another stage to the breech end of the single-stage gun described in reference 1. Hence, it is not known if the proportions are close to the optimum. The construction of the gun and its major dimensions are shown in figure 2. Figure 3 is a photograph of the gun mounted for use in connection with the Atmosphere Entry Simulator. The two shock tubes may be seen in the foreground while the launch tube extends through an opening in the far wall of the gun room.

The first shock tube was constructed from a section cut from the breech end of a 5-inch naval gun. A mild-steel liner was used to reduce the bore to 4 inches. The second shock tube of 2-1/4-inch bore was made of two concentric tubes of alloy steel with a shrink fit to withstand the high pressures developed near the entrance to the launch tube. Openings are provided near the midpoint of the length of each shock tube for charging the tubes with helium. Remotely operated high-pressure valves are located close to the openings. The launch tube consists of three standard 20-mm test barrels coupled together. All tubes were smooth-bored. The supports for the various tubes were made adjustable both vertically and laterally. Friction in these supports is the only axial restraint provided; however, no axial movement of the gun upon firing has been noted.

The couplings were constructed so that the two shock tubes could be pushed back a few inches with a hydraulic jack allowing the second shock tube to be rolled to one side on supports, giving access to all tubes for cleaning and inspection. Pressure seals of the synthetic-rubber "O-ring" type were employed at all joints except where the piston and projectile were sealed against the initial helium pressure. There compression of the plastic shear discs between the steel surfaces proved adequate. Steel rings forming bellmouthed entrances to the second shock tube and to the launch tube were provided.

The firing mechanism is incorporated in a steel plug which is screwed into the end of the first shock tube and serves to close the breech. It is arranged to fire either electrical or percussion type primers. The primer is inserted in a steel plug that serves as a base on which the powder charge can be retained by a paper container attached with scotch tape. A rather long primer which extends nearly the full length of the powder charge is employed because it is believed to give more reproducible results in cases such as the present where the powder is not confined by the presence of a heavy projectile. Trials with a short primer indicated that about 10 percent more powder was required to develop a given breech pressure. A relatively fast burning powder is used, much faster than would normally be used in a conventional gun of this bore. A typical charge is 900 grams of IMR 4198, a smokeless powder intended for use in rifles.

The piston which operates in the second shock tube is a cylinder machined from plastic rod. Figure 4 is a photograph of a piston and the nylon shear disk. A clearance of a few thousandths of an inch on diameter is allowed, and no special seals are provided. Two types of plastic materials found to be satisfactory for this use were "Kish" a resilient epoxy resin, often used as material for impact dies, and a fabric-reinforced phenolic resin, such as Bakelite or Micarta. When these plastics were used, the piston usually remained intact and formed a seal at the entrance to the launch tube, retaining the powder gases and helium from the first shock tube.

The sequence of operations in firing the gun is as follows: The shock tubes and launch tube are coupled together with the projectile and piston in place. The primed charge is inserted in the breech and the breech plug screwed into place. All further operations are performed from another room separated from the gun by a heavy concrete wall. The shock tubes are then evacuated to remove the air, which being of higher molecular weight than helium might detract from the performance and which containing oxygen might promote corrosion. The shock tubes are then filled with helium to the desired pressure, the system is checked for leakage by noting if the pressure tends to fall, and the valves are closed. Normally, firing is then accomplished by discharging an electrical capacitor through the primer. In case it is desired to fire by means of a percussion primer, a spring-loaded pin is cocked by a manually operated cable and the pin is tripped by a solenoid.

Many types of projectiles have been fired from the gun. These were mostly simple shapes machined from various plastics, some containing reinforcement such as glass fibers. The projectiles varied in weight from 2.5 to 18 grams. They were machined to fit the bore of the launch tube with a clearance of about 1/1000 of an inch. Figure 5 is a photograph of representative projectiles. At the left is seen a plastic projectile with integral shear disk. At the right is an aluminum projectile with a separate plastic shear disk. The intervening projectiles are machined from various plastics and are fired with the use of a separate shear disk. At the high launching pressures required to obtain high velocity, some of the plastic projectiles tended to break up in the launch tube. The materials found most suitable for launching at high velocity were polyethylene and Ethocel; however, the range of plastics available has not been completely explored.

The Atmosphere Entry Simulator, for which the gun serves as model launcher, provides a firing range 40 feet long with 12 stations at which the time of arrival of the projectile can be determined and at which spark shadowgraphs can be taken of the projectile in flight. At each station a thin beam of light falls on a photocell. Interruption of this light beam by the projectile controls an electronic counter and fires the shadowgraph spark. Thus the apparatus serves to measure the muzzle velocity and to determine whether the projectile is intact after leaving the gun. It is believed that the muzzle velocities quoted later are accurate within ±200 feet per second. Maximum pressures occurring during the firing cycle were measured with copper crusher gages located as indicated in figure 2, at the breech of the first shock tube, at the muzzle end of the first shock tube, and at the muzzle end of the second shock tube. These gages record only the maximum pressure and are thought to have rather poor accuracy in measuring the suddenly applied and highly transient pressures encountered in this application. A further uncertainty exists in the case of the gage at the muzzle end of the second shock tube. This gage is located 3.84 inches from the entrance to the bellmouthed washer, and it is possible that in some cases the piston had passed this gage hole before peak pressure was reached.

Some of the rounds reported herein were fired into still air at an absolute pressure of 3 mm of mercury, the air pressure in the launch tube being at this same value. Other rounds were fired with the Atmosphere Entry Simulator operating. In the latter case the air pressure in the launch tube was maintained at a low, but unknown, pressure by firing through a blast tank connected to a vacuum system. In both cases it is believed that the air pressure in the launch tube was so low that it had a negligible effect on the muzzle velocity.

PERFORMANCE OF THE GUN

The loading conditions of the gun include a number of variables: the weight of powder, burning speed of the powder, the initial helium pressure in each shock tube, the piston weight, and the projectile weight. For each projectile weight there must be an optimum combination of the other loading conditions which, without exceeding the allowable pressures in the gun, will give the highest velocity. Sufficient trials have not been made to optimize these conditions, but rather the gun was put into service after only the trials required to establish loading conditions giving satisfactory performance for launching models in the Atmosphere Entry Simulator. It is expected that some improvement in performance could be attained, particularly with the heavier projectiles, by systematic tests to determine the optimum loading conditions for projectiles of various weights.

The performance of the gun is illustrated by the data of table I where the results from a number of rounds are listed. These rounds include the highest muzzle velocities obtained with each projectile weight as well as a variety of loading conditions for projectiles of constant weight. The results of these firings indicate that the gun is capable of launching very light projectiles at speeds of over 20,000 feet per second, the highest obtained being 22,670 feet per second with a projectile weight of 2.46 grams. With heavier projectiles the maximum velocities were lower, 11,600 feet per second being obtained with a projectile weighing 17.95 grams. A separate nylon shear disk was used to restrain the projectile for all rounds listed. The center portion of the disk was launched with the projectile, and its weight (0.43 grams) is included in the tabulated projectile weights.

Figure 6 shows the variation of the peak pressure at the breech P_B, and the peak pressure at the muzzle end of the first shock tube P_C, with powder charge for an initial helium pressure P_1 of 300 psi. It will be noticed that P_B and P_C are about equal and range from 10,000 to 20,000 psi. There is a considerable scatter in the data which is believed to be due in part to the nonrepeatable character of the powder burning process and in part to the poor accuracy of the copper crush gages in measuring the highly transient pressure peaks. The powder burning process would be expected to be less repeatable in this gun, where the burning takes place in a large chamber filled with gas, than in a conventional gun where the powder is confined by the presence of a heavy projectile.

In figure 7 is shown the variation of the peak pressure at the muzzle end of the second shock tube P_L, and the muzzle velocity of the projectile with powder charge, for two values of the initial helium pressure P_2, in the second shock tube. The peak pressure and velocity both show some variation for nominally identical loading conditions. This variation may be attributed to the causes noted above. It is interesting to observe that while the values of P_L obtained with an initial helium pressure P_2 of 250 psi were lower than those obtained with a P_2 of 300 psi, the corresponding muzzle velocities fall on about the same curve. A higher temperature of the helium compressed from the lower initial pressure would explain this result.

The pressures plotted in figures 6 and 7 and those listed in table I indicate that the first shock tube is subjected to only moderate pressures, but the muzzle end of the second shock tube and the adjacent portion of the launch tube are exposed to a pressure which may exceed 100,000 psi. This pressure is highly transient and the volume of gas at this pressure is small; hence no large factor of safety need be applied in designing the tubes and no great damage is anticipated in case of a failure.

The maximum muzzle velocities obtained with projectiles of various weights are plotted in figure 8. The loading conditions for these rounds were not constant but the plotted velocities serve to indicate the performance which can be obtained with projectiles of various weights. For comparison there is included the calculated variation of velocity with projectile weight for a helium pressure of 75,000 psi and a helium temperature of 10,000° R. This curve was calculated by the theory of reference 2 which assumes an infinitely long chamber of the same diameter as the launch tube. The conditions in the present gun do not conform to these assumptions but the trend of variation of velocity with weight is similar except that the experimental velocities drop faster with increasing weight than the theoretical values. The heavier projectiles are accelerated more slowly and require maintenance of high pressure at the entrance to the launch tube for a longer period. This suggests that some improvement in performance with the heavier projectiles might be obtained by optimizing the values of powder burning rate, piston weight, and initial helium pressures.

EXPERIENCE WITH GUN

At the time of writing, the gun has been in operation for about a year and over 400 rounds have been fired. The projectiles have been principally cylinders and cone-cylinders with rounded noses, made of various plastics. The projectiles usually fly straight and do not tumble; however, tumbling has been experienced at times. Some difficulty has been encountered with projectiles breaking up during launching, but many types of plastics have been fired successfully. In general, the plastics having high impact strength showed the least tendency to break up during launching. Nylon projectiles were never launched intact at speeds over 13,000 feet per second with this gun, although this material has been launched successfully from other guns. The only metallic projectile fired was an aluminum alloy cylinder, one caliber long (round 91, table I). It was launched intact.

The velocity obtained with the gun was not repeated exactly on rounds with apparently identical loading conditions. A scatter of ±500 feet per second was regularly encountered. Occasionally there was a larger deviation which could usually be traced to a leaking pressure seal. Break-up of the piston did not appear to adversely affect the muzzle velocity; hence, it is concluded that the break-up occurred when the piston reached the end of the second shock tube, after the projectile was launched.

The gun has been operated without the use of a piston. In such cases the measured peak pressures P_B, P_C, and P_L were all of about the same magnitude, meaning that all parts of the gun would be subjected to a pressure about equal to the peak launching pressure. Also the size of the powder charge required to develop the required value of P_L became alarming. The piston has therefore been employed for all high velocity rounds.

It has been necessary to replace certain parts of the gun which are subject to erosion by the hot gases. The breech section of the launch tube and the two bellmouthed washers have required replacement after about a hundred rounds. These parts may be replaced without undue expense; however, the bore of the second shock tube has become so eroded after 400 rounds as to need replacement. This is a more expensive part and, as the erosion is confined to the breech end, it would appear wise to provide a replaceable liner a foot long at this point.

It was found that proper alinement of the three sections of the launch tube was necessary to launch the projectiles intact. An alinement telescope was used for this purpose. The cleanliness of the bore was also found to be important. A portable rig was provided to hone the launch tube without removing it from its supports and without disturbing its alinement. This proved a convenient means of cleaning the bore and maintaining the joints flush between sections.

A crew of three men require about one hour to disassemble, clean, reassemble, and load the gun. Hence, if only the gun need be considered, six or eight rounds a day might be fired. In the present application much other apparatus and instrumentation must also be serviced at each round and three rounds per eight-hour day is the usual rate.

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CONCLUDING REMARKS

The gun which has been described has proved a practical means of launching simple projectiles of light materials at speeds of over 20,000 feet per second. As such it provides a useful tool for aerodynamic, heat transfer, and ablation studies. It seems likely that the gun could be used to launch small pellets of dense materials for impact investigations if a suitable sabot of light material could be developed. This has not yet been attempted with this gun.

The dimensions of the present gun were selected rather arbitrarily and it is not known if the proportions are close to the optimum. It is expected, however, that a geometrically similar gun of different size would give the same performance. It is believed that the powder burning rate should be scaled with the size of the gun; that is, a larger gun should use a slower burning powder.

The gun is relatively simple to operate and its construction need not be expensive. Only the launch tube bore needs to be finely finished and carefully alined. The pressures are quite moderate in all parts of the gun except for a small region including the muzzle end of the second shock tube and the breech end of the launch tube.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Oct. 20, 1959

REFERENCES

1. Neice, Stanford E., Carson, James A., and Cunningham, Bernard E.: Experimental Investigation of the Simulation of Atmospheric Entry of Ballistic Missiles. NACA RM A57I26, 1957.

2. Charters, A. C., Denardo, B. Pat, and Rossow, Vernon J.: Development of a Piston-Compressor Type Light-Gas Gun for the Launching of Free-Flight Models at High Velocity. NACA TN 4143, 1957.

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TABLE I.- DATA FROM REPRESENTATIVE ROUNDS

Round no.	Powder type	Charge weight, grams	Piston weight, grams	Initial pressures, psi		Peak pressures, psi			Projectile		Muzzle velocity, ft/sec
				P_1	P_2	P_B	P_C	P_L	Material	Weight, grams	
72	IMR4895	835	127	300	200	13,400	11,400	51,900	Ethocel	4.81	17,850
74	IMR4895	900	127	300	250	14,000	14,500	70,400	Ethocel	4.81	18,650
76S	IMR4895	950	127	300	250	15,300	17,300	77,500	Ethocel	4.81	18,800
79S	IMR4895	1000	127	300	250	21,200	19,700	89,000	Ethocel	4.81	19,500
172S	IMR4895	750	127	300	300	11,000	9,200	57,600	Ethocel	4.81	15,300
72S	IMR4895	910	127	300	300	14,400	17,100	87,000	Ethocel	4.81	18,600
70	IMR4895	900	85	600	300	11,200	13,000	77,300	Ethocel	4.81	16,370
162S	IMR4895	1000	127	600	300	15,700	20,000	85,500	Fluorogreen-T	6.43	18,000
57	IMR4895	1100[a]	127	600	300	15,300	15,100	83,500	Fiberglas-Resin	8.60	17,380
131S	IMR4895	1000	160	600	300	16,700	18,600	96,000	Fluorogreen-T	9.44	15,500
90	IMR4198	900	127	300	250	12,600	14,300	71,700	Polyethylene	2.46	22,670
88	IMR4198	900	127	300	250	19,600	21,700	85,500	Polyethylene	3.46	21,840
91	IMR4198	900	127	600	300	15,600	22,500	115,000	Aluminum	17.95	11,600

[a]Short primer used on round no. 57.

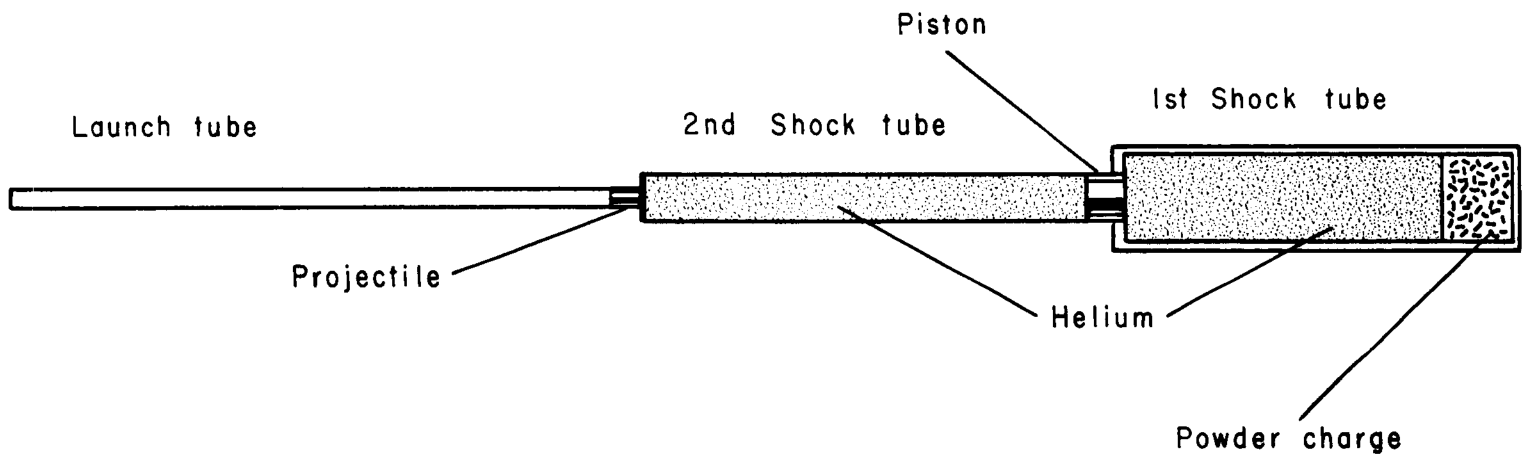

Figure 1.- Schematic diagram of two-stage shock-compression light-gas gun.

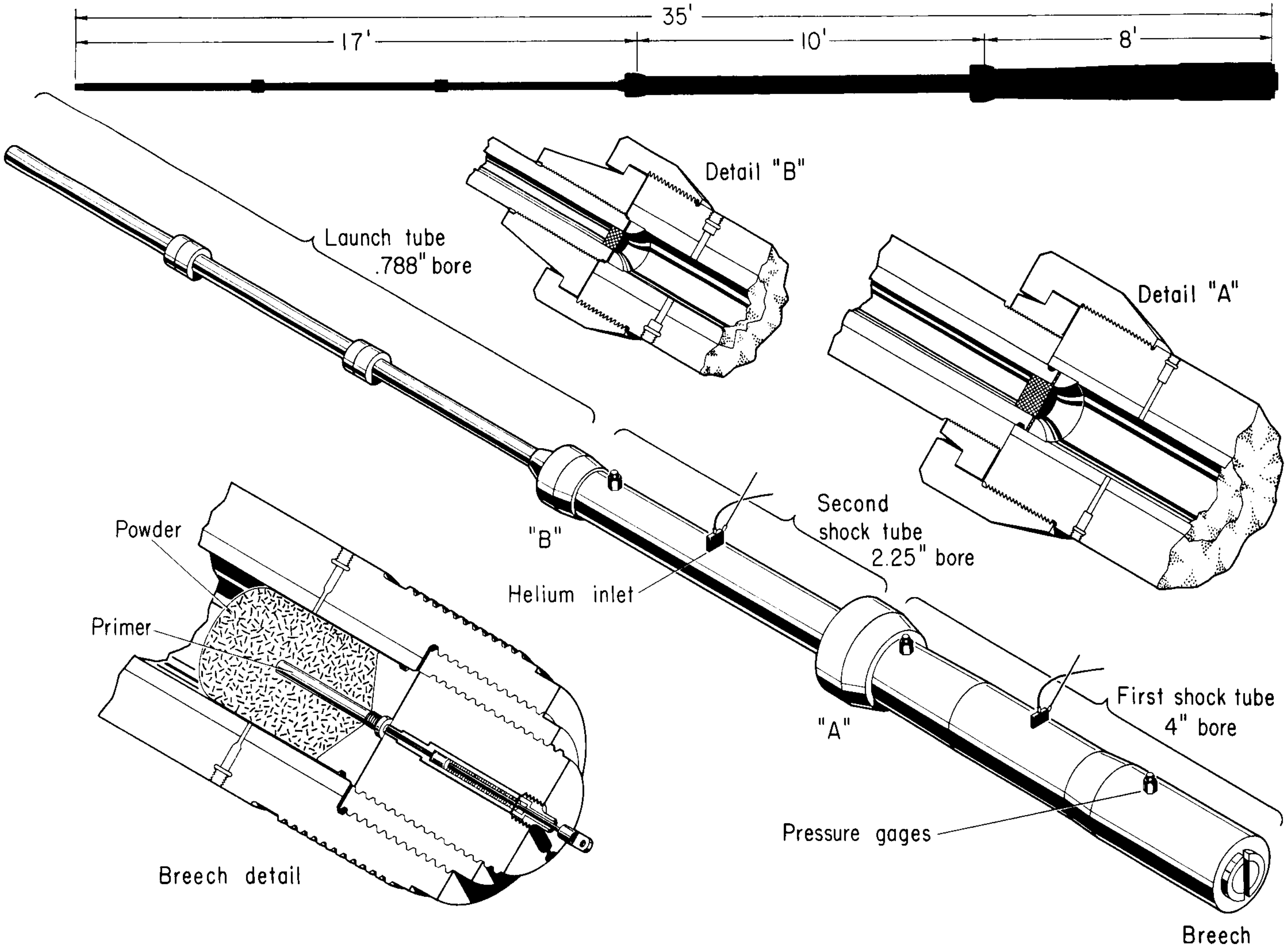

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Figure 2.- Sketch of gun showing construction and principal dimensions.

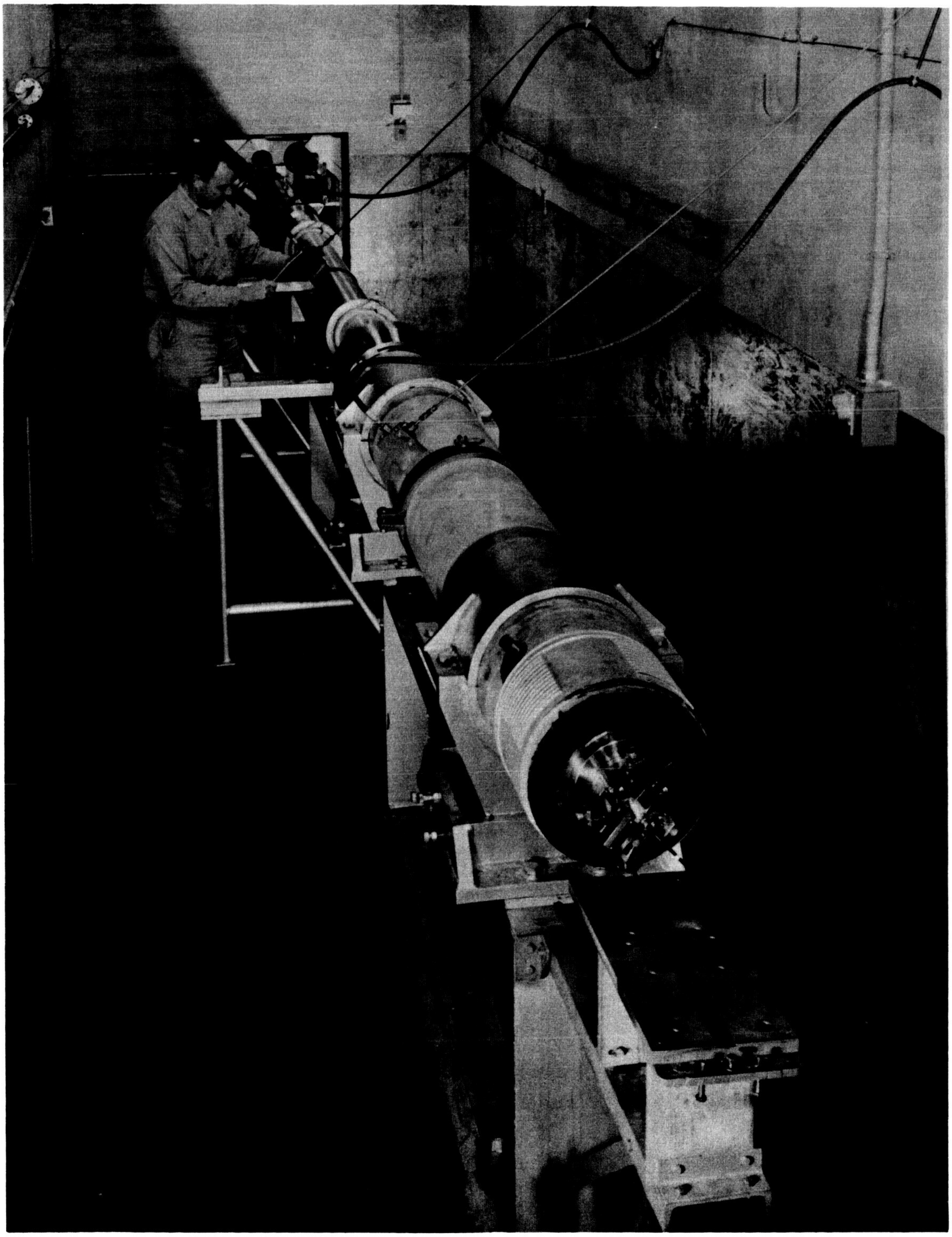

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Figure 3.- Photograph of gun mounted for use.

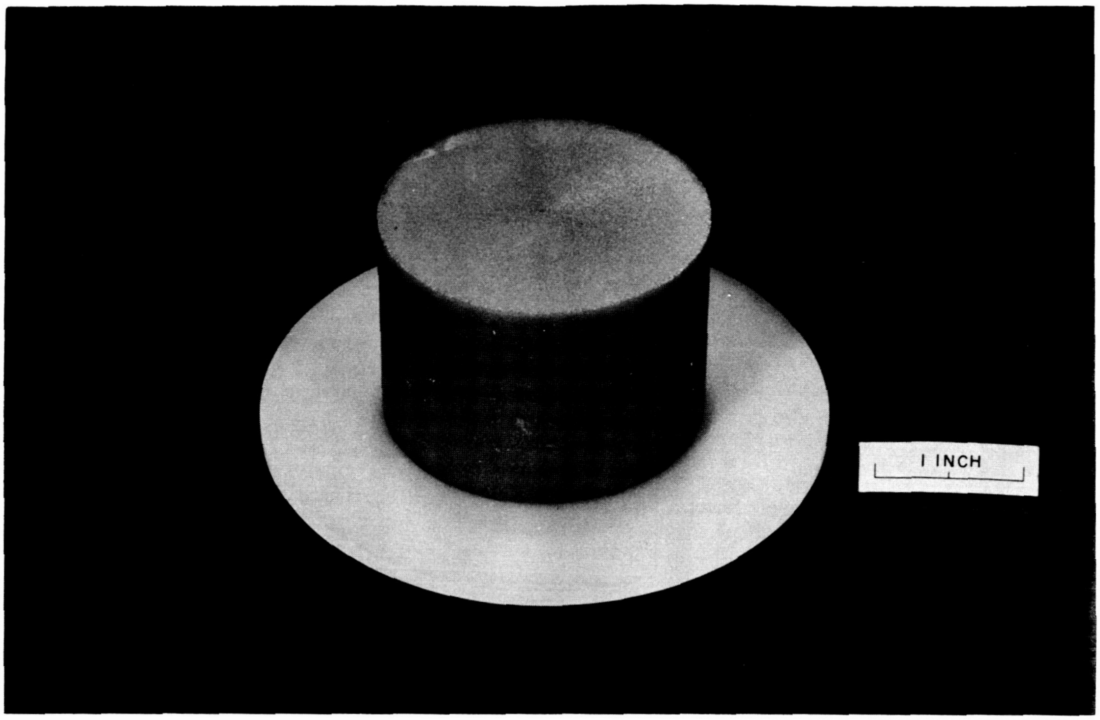

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Figure 4.- Plastic piston and shear disk.

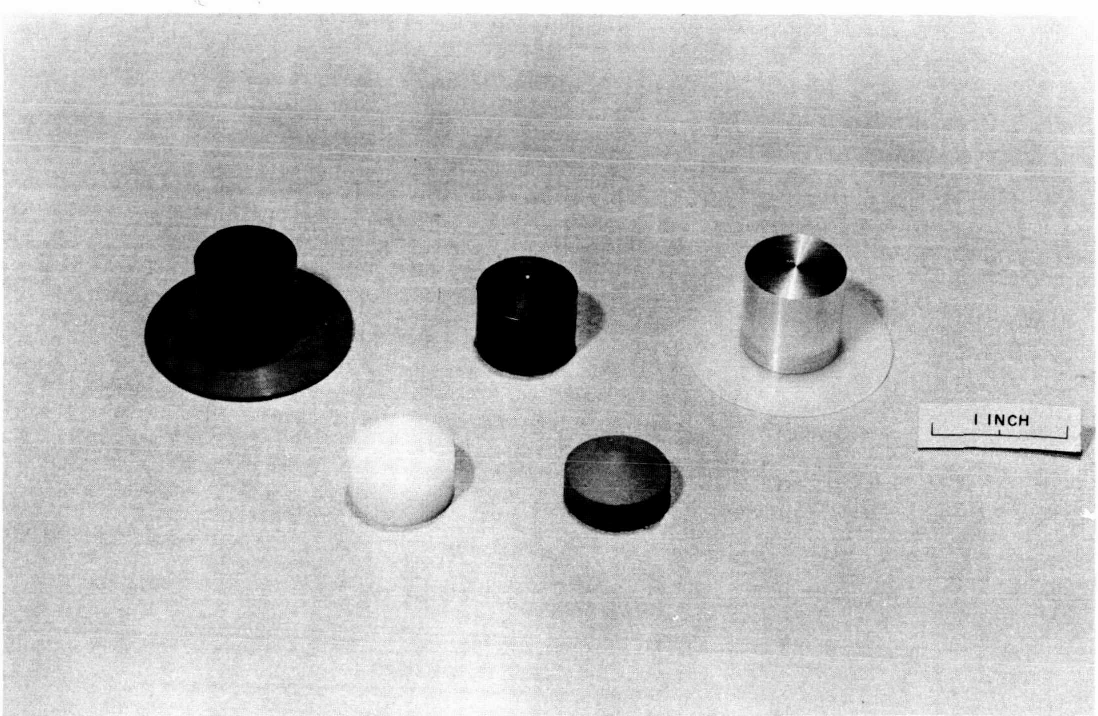

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Figure 5.- Representative projectiles.

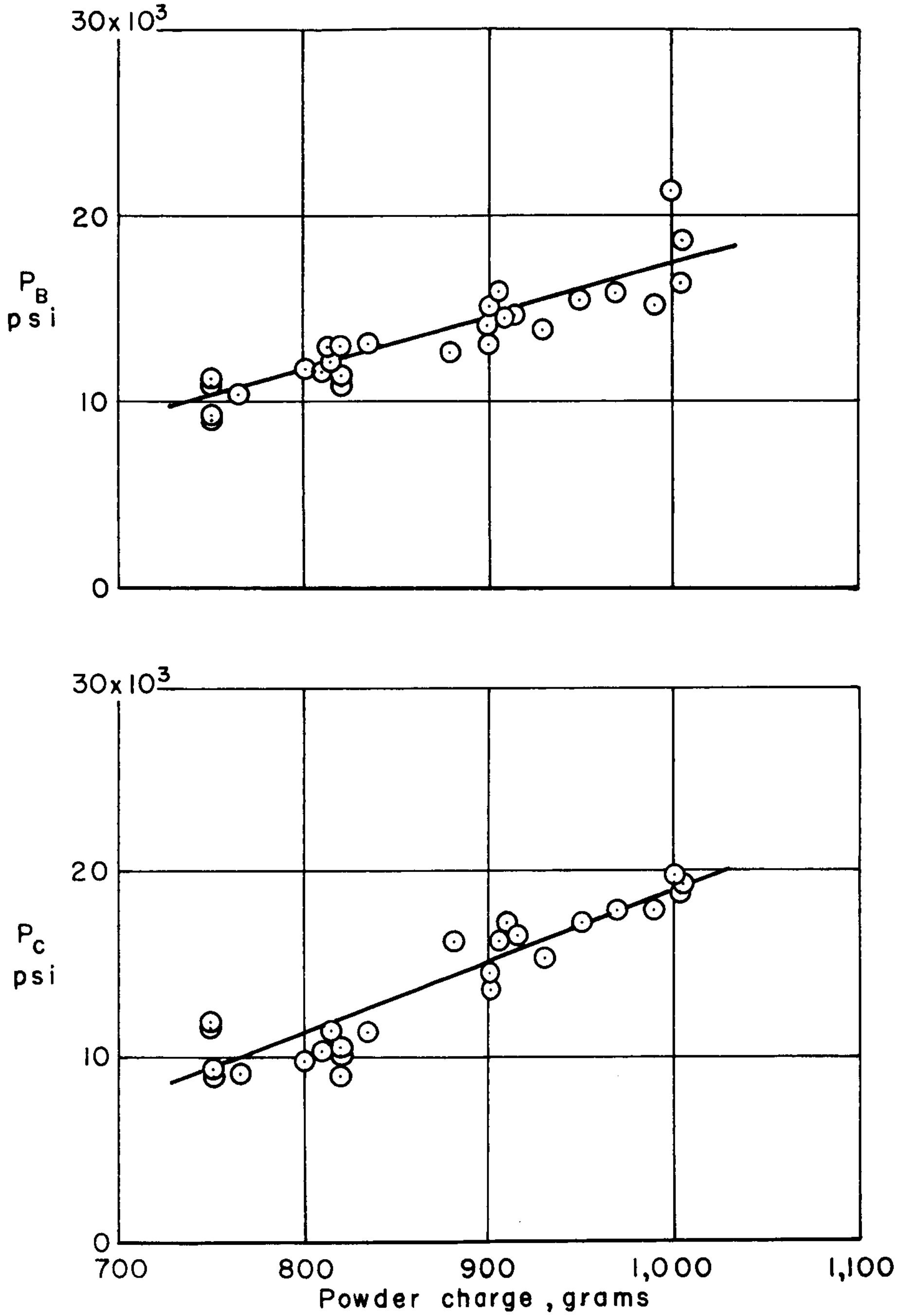

Figure 6.- Variation of peak pressures in first shock tube with powder charge; IMR 4895 powder, P_1 = 300 psi, 127 gram piston.

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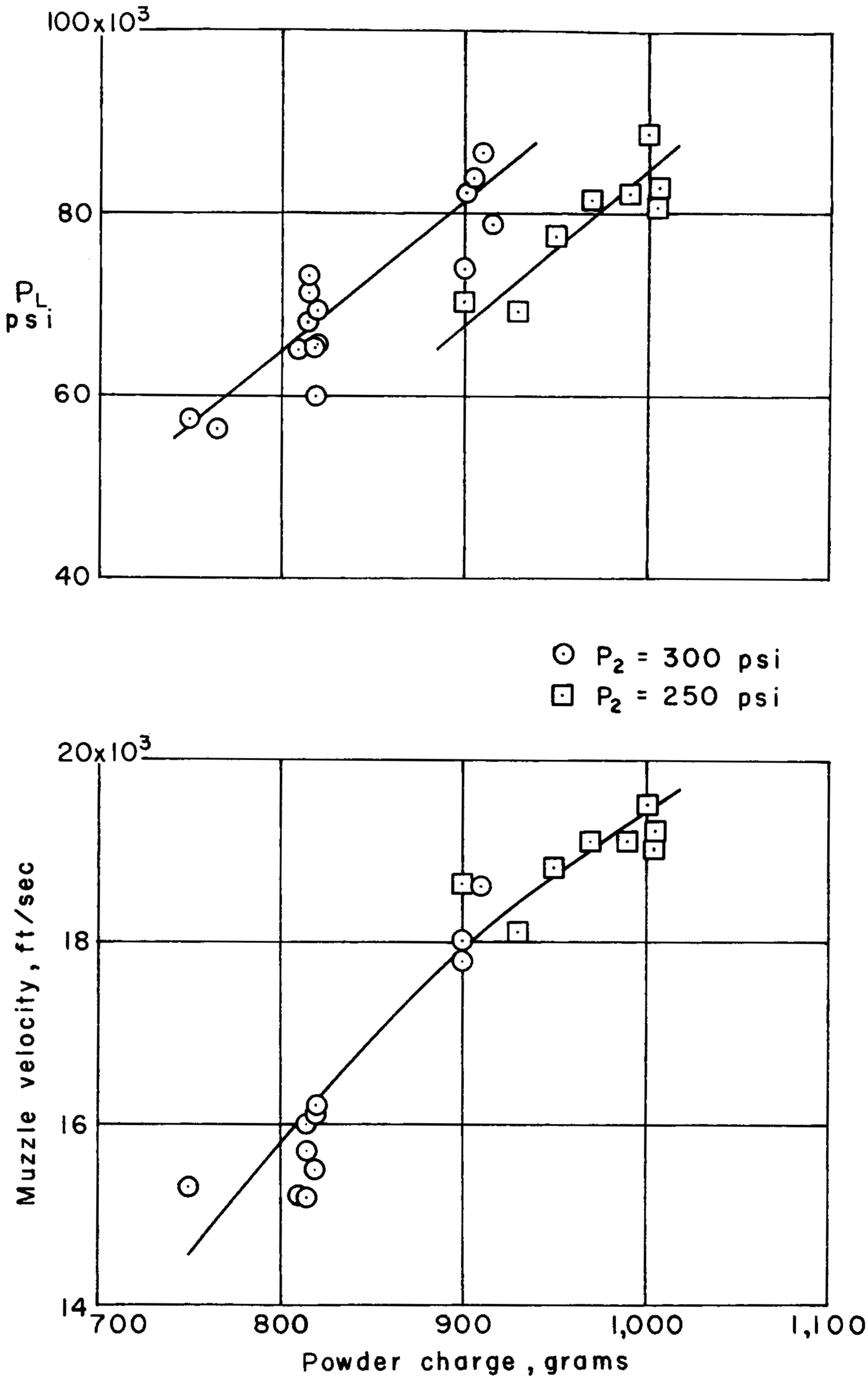

Figure 7.- Variation of peak pressure at muzzle end of second shock tube and muzzle velocity with powder charge; IMR 4895 powder, P_1 = 300 psi., 127 gram piston, 4.81 gram projectile.

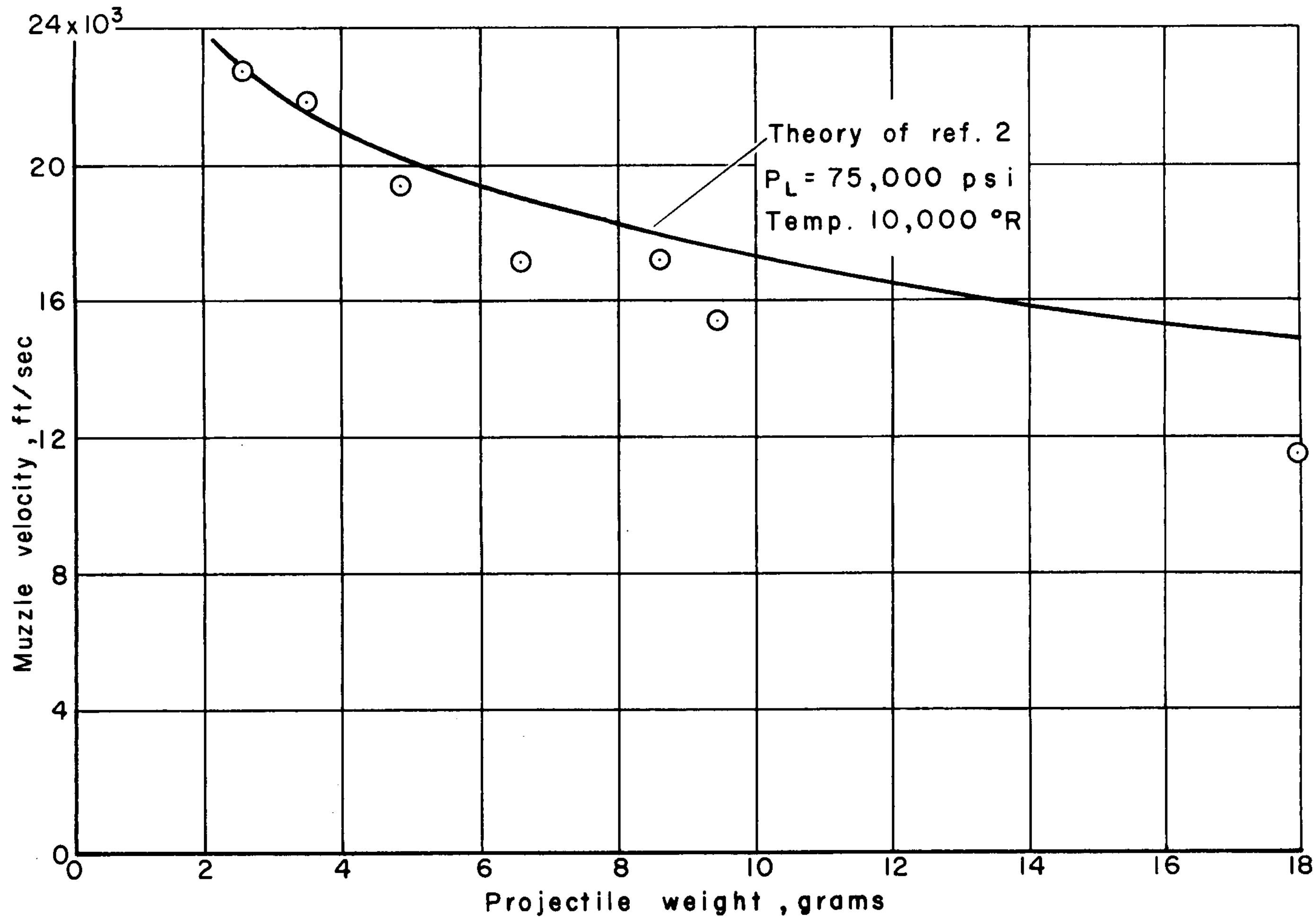

Figure 8.- Maximum muzzle velocities obtained with various projectile weights; loading conditions not constant.